Please add new claim 136 as follows:

A8

136. (New) A method of modifying a semiconductor compound or alloy comprising host atoms in a host crystal lattice and characterized by a conduction band, a valence band and a bandgap there between, the method comprising isoelectronically co-doping the semiconductor compound or alloy with a first isoelectronic dopant comprising atoms that form isoelectronic electron traps in the host crystal lattice that behave as deep acceptors and with a second isoelectronic dopant comprising atoms that form isoelectronic hole traps in the host crystal lattice that behave as deep donors at sufficiently high concentrations to form at least one impurity band that merges with one of the conduction and valence bands, whereby the effective bandgap of the semiconductor compound or alloy is modified.

REMARKS

Claims 1-135 were pending in the application. The examiner allowed claims 22-28, 50-58, 67-76, 84, and 106-118, rejected claims 1, 29, 30, 33, 34, 39, 40, 45, 59-65, 77-82, 85-88, 119, 120, and 132-135, and objected to 2-21, 31, 32, 35-38, 41-44, 46-49, 66, 83, 89-105, and 121-131. The applicant has now amended claims 1, 2, 29, 30, 77, 81, 85, 119, and 132 and added new claim 136. Claim 79 has been cancelled. Attached hereto is a markup version of the changes made to the specification and claims by the current amendment. The applicant believes that all of the pending claims 1-78, 80-136 are now either already allowed or in allowable form, as explained in more detail below.

Regarding the Specification:

Most of the changes in the specification are to correct format, punctuation, and word processing errors, which are self-explanatory. The addition of the word "preferably" on page 8, line 2, is made to avoid any perception of inconsistency with page 17, line 2. The phrase, "as the host element they replace" added to the sentence on page 8, line 20, is obvious and well-known in the art as well as inherent in the rest of the specification (see, e.g., page 9, lines 7-9, 10-12, 20-22; page 10, lines 204, 5-8; page 14, lines 1-28; page 15, lines 1-28; page 16, lines 1-14, etc.), but it may be helpful to complete that sentence better.

Regarding Claim 1:

The examiner rejected claim 1 under 35 U.S.C. § 102(b) as anticipated by, or, in the alternative, under 35 U.S.C. §103(a) as being obvious over, Kuznetsov, et al. Specifically, the examiner asserts that, "the functional language in claim 1 does not structurally distinguish over Kuznetsov, unless applicant can prove that the same function does not occur in Kuznetsov."

The proof required by the examiner is in the Kuznetsov, et al., article itself. Specifically, the photoluminescence spectra and electroluminescense spectra shown in Kuznetsov's Figures 1, 2, 3, and 4 clearly demonstrate only N impurity-to-valence transitions and not band-to-band transitions. These distinctions are well-known to persons skilled in the art, and the impurity-to-valence transition character of the spectra in the Kuznetsov, et al., Figures 1, 2, 3, and 4 is easily observable and readily discernable to persons skilled in the art. Those donor-acceptor like transitions from N impurity levels to valence band in Kuznetsov, et al., show characteristically weak optical absorption in the "impurity regime," where density of initial states and final states for such transitions is low. Therefore, there is no bandgap modification shown in, or suggested by, Kuznetsov, et al.

This observation is also consistent with the low N-dopant concentrations with which Kuznetsov, et al., were dealing. Even at their highest N concentration of $5x10^{18}cm^{-3}$ (see Kuznetsov, et al., p. 417, second paragraph), i.e., 0.002%N, in GaP, impurity bands, if any, would have barely begun to form and would have certainly not have merged with the edge bands, as would be required to modify the bandgap of the semiconductor compound or alloy. Consequently, Kuznetsov, et al., did not observe, have data showing, or even discuss any formation of strongly overlapping impurity bands or any of the associated features of this invention, such as behavior resembling that of a direct bandgap semiconductor from ordinarily indirect bandgap GaP, improved carrier lifetime, and improved carrier mobility. (See, e.g., Specification at pages 12-13).

In order to modify the bandgap of their GaP and to obtain these associated features, Kuznetsov, et al., would have needed a N concentration in the host lattice several orders of magnitude higher than their maximum N concentration of $5x10^{18}cm^{-3}$. However, there is no motivation or suggestion in any of the prior art, including Kuznetsov, et al., to

isoelectronically co-dope their GaP to sufficiently high concentrations to actually modify the bandgap of their GaP, let alone how such high concentrations could be attained. Kuznetsov, et al., used liquid epitaxy to grow their semiconductor material from a Ga + Bi melt, which was then doped with N from an ammonia vapor above the melt and exposed to P in a vacuum from a ZnP_2 source. Even though they used melts containing as little as 5 at. % Bi to as much 45 at. % Bi, Kuznetsov, et al., never got more than $5x10^{18}cm^{-3}$ N, and there is no teaching or suggestion as to how their N concentration could be further increased, let along by several orders of magnitude to the levels shown by the present invention for actually modifying the bandgap of the semiconductor material. It is well-established that, in the absence of some incentive or suggestion in the prior art to modify such prior art teachings to obtain the applicant's claimed invention, an obviousness rejection under 35 U.S.C. § 103 is improper. *In re Laskowski*, 10 U.S.P.1.2d 1397, 1398 (Fed. Cir. 1989). Further, there must be a reason or suggestion in the prior art for selecting the procedure used, other than the knowledge learned from the applicant's disclosure, for an obviousness rejection under 35 U.S.C. § 103 to be proper. See, *In re Dow Chemical Co.*, 5 U.S.P.Q.2d 1529, 1531-32 (Fed. Cir. 1988).

Applicant has amended claim 1 to put more of a quantitative aspect to the claim language consistent with the specification and with the distinctions described above. Therefore, claim 1 is now believed to be allowable over Kuznetsov, et al., under both 35 U.S.C. § 102(b) and 32 U.S.C. § 103(a).

<u>Regarding Claims 2 – 21:</u>

Claim 2 was deemed by the examiner to be allowable if rewritten in independent form including all the limitations of the base claim. Therefore, claim 2 is amended into independent form and to include all the limitations of its base claim. Consequently, claim 2, as now amended, should be allowable, and dependent claims 3 - 21 should also be allowable.

<u>Regarding claims 22 – 28:</u>

Claims 22 – 28 are already allowed, as noted above.

<u>Regarding claim 29:</u>

Claim 29 was rejected by the examiner under 35 U.S.C. § 102(b) as anticipated by, or, in the alternative, under 35 U.S.C. § 103(a) as being obvious over, Kuznetsov, et al., for the

same reasons as his rejection of claim 1. Therefore, the applicant's comments regarding Kuznetsov, et al., and claim 1 also apply to claim 29. Likewise, Applicant has also amended claim 29 to have more of a quantitative aspect to the claim language similar to amended claim 1. Consequently, claim 29 is now believed to be allowable over Kuznetsov, et al., under both 35 U.S.C. § 102(b) and 35 U.S.C. § 103(a).

Regarding claim 30:

Claim 30 was rejected under 35 U.S.C. § 102(b) as anticipated by, or, in the alternative, under 35 U.S.C. § 103(a) as being obvious over, either Kuznetsov, et al., or Yamamoto. The rejection of claim 30 based on Kuznetsov, et al., is for the same reasons as his rejection of claim 1. Therefore, the applicant's comments above regarding Kuznetsov, et al., and claim 1 also apply to claim 30, and applicant has amended claim 30 in a manner similar to claim 1. Specifically, claim 30 is amended to recite modification of the effective bandgap by sufficient isoelectronic co-doping to lower the effective bandgap, which is neither shown nor suggested by Kuznetsov, et al. Therefore, amended claim 30 is believed to be allowable over Kuznetsov, et al., for the same reasons as claim 1.

Contrary to the examiner's assertion on page 3 of the Office Action, claim 30 does structurally distinguish over Yamamoto. Claim 30 recites isoelectronic co-doping with isoelectronic dopants. Yamamoto, et al., deal with co-doping, but with charged dopants, not isoelectronic dopants. Their ZnO is a Group II – VI alloy, while their A1, Ga, or In species dopants are Group III and their N species dopant is Group V, thus not isoelectronic or isovalent with the constituent elements (cation or anion) of the host semiconductor. Instead, the dopant impurities of Yamamoto, et al., have one more or one fewer electron than the host elements they replace, which are ionized, thus charged, in the host with either a net positive or a net negative charge, respectively, and they behave as shallow impurity centers in the host. In contrast, as recited in claim 30, applicant's isoelectronic impurities behave as deep acceptors and deep donors in the host semiconductor. The physics describing these two different types of behavior is entirely different. It is the isoelectronic electron trap-induced impurity levels generating states with localized electrons just below the conduction band edge, i.e., isoelectronic deep acceptors, and the isoelectronic hole trap-induced impurity levels generating states with localized holes just above the valance band edge, i.e.,

isoelectronic deep donors, that cause the massive conduction band bowing, thus lowering the effective bandgap, in semiconductor materials according to this invention. See, e.g., specification, pages 14-16. Nothing in Yamamoto, et al., teaches or suggests this structure or this result, as recited in amended claim 30. Therefore, claim 30 is also allowable over Yamamoto under both 35 U.S.C. § 102(b) and 35 U.S.C. § 103(a).

Regarding claims 31 – 32:

With allowance of amended claim 30, the examiner's objections to dependent claims 31 and 32 will be moot.

Regarding claims 33 – 34:

Dependent claims 33 and 34 were rejected, like claim 30, under 35 U.S.C. § 102(b) and 35 U.S.C. § 103(a) based on Kuznetsov, et al., for the same reasons as claim 1. These claims 33 and 34 are deemed to be allowable now for the same reasons as claims 1 and 30, explained above.

Regarding claims 35 – 38:

With allowance of claims 30 and 33 – 34 for the reasons explained above, the examiner's objections to claims 35 – 38 will be moot.

Regarding claims 39 – 40:

Dependent claims 39 and 40 were rejected under 35 U.S.C. § 102(b) and 35 U.S.C. § 103(a) based on Kuznetsov, et al., for the same reasons as claims 1, 30 and 33 – 34. These claims 39 and 40 are deemed to be allowable now, for the same reasons as claims 1 and 30, explained above.

Regarding claims 41 – 44:

With allowance of claims 30, 33 – 34, and 39 – 40 for the reasons explained above, the examiner's objections to dependent claims 39 – 40 will be moot.

Regarding claim 45:

Claim 45 was rejected under 35 U.S.C. § 102(b) and 35 U.S.C. § 103(a) based on Yamamoto for the same reasons as claim 30. Therefore, claim 45 is now deemed to be allowable for the same reasons as explained above regarding claim 30.

Regarding claims 46 – 49:

With allowance of claims 30 and 45 for the reasons explained above, the examiner's objections to dependent claims 46 – 49 will be moot.

Regarding claims 50 – 58:

Claims 50 – 58 are already allowed.

Regarding claims 59 – 65:

The examiner rejected claims 59 – 65 under 35 U.S.C. § 103(a) as being unpatentable over Kuznetsov in view of applicant's prior art admissions. While applicant certainly admits that the use of tandem solar cell structures to improve efficiency is well-known in the prior art, as asserted by the examiner, there is nothing in that admission, either alone or in combination with Kuznetsov, et al., that makes the invention recited in claims 59 – 65 obvious to a person having ordinary skill in the art. On the contrary, applicant's independent claim 59 recites not only a Si bottom cell with a bandgap of about 1.1 eV, but also a top cell comprising GaP that is isoelectronically co-doped with a deep acceptor element and a deep donor element *to have an effective bandgap of about 1.75 eV.* As explained above in regard to claim 1, Kuznetsov, et al., do not show or suggest any modification of the effective bandgap of GaP to anything *different than its usual, ordinary 2.26 eV.* Thus, contrary to the examiner's assertion, it would not be obvious to one of ordinary skill to have practiced a solar cell with the GaP:N:Bi material from Kuznetsov in order to efficiently collect photons of the same energy as the material bandgap of 1.75 eV recited in applicant's claim 59. Persons skilled in the art know that the 2.26 eV bandgap of Kuznetsov's GaP:N:Bi is incapable of collecting photons of the same energy as a 1.75 eV material bandgap, and neither Kuznetsov, et al., nor ay other prior art teaches or fairly suggests how one could lower their GaP:N:Bi bandgap from 2.26 eV down to about 1.75 eV. No prior art reference shows or even suggests a GaP:N:Si semiconductor material with a 1.75 eV bandgap. Only the applicant's invention in this patent application teaches how GaP:N:Bi can have an effective bandgap of about 1.75 eV. Therefore, independent claim 59 is clearly allowable, as are dependent claims 60 – 65.

Claim 65 further recites that the isoelectronically co-doped GaP:N:Bi crystal lattice is lattice matched to the Si substrate, which is novel and non-obvious for the reasons explained below regarding claims 77 – 82.

Regarding claim 66:

With allowance of claims 59 – 65 for the reasons explained above, the examiner's objection to dependent claim 66 will be moot.

Regarding claims 67 – 76:

Claims 67 – 76 are already allowed.

Regarding claims 77 – 83:

The examiner asserted that applicant's claims 77 – 83 would be obvious, thus are rejected under 35 U.S.C. § 103(a) because, "GaP on Si is well-known in the solar art, as their lattice constants are similar and Si is used as a bulk substrate material for solar cells." See Office Action, page 3, lines 4 – 6. The applicant disagrees with these assertions by the examiner. GaP on Si is not well-known or even practiced in the solar cell art, and certainly not in any practical solar cell structure, for at least two very good reasons.

First, solar cells require a direct bandgap absorbing semiconductor on top of a Si substrate cell, whereas GaP has an indirect bandgap. In order for an indirect bandgap GaP to absorb sunlight above the bandgap energy, it would require the GaP layer to be about 100 μm thick, whereas typical absorber layer thickness in a solar sell is about 1 μm. Epitaxial growth of such a thick GaP absorber layer would be prohibitively long and expensive.

Second, while GaP is closely lattice-matched to Si (0.37% compressive misfit strain at room temperature), as acknowledged by applicant in the Specification, page 18, lines 21 – 22, there is still a significant cracking problem due to the differences in coefficients of expansion between GaP and Si. This problem manifests itself when GaP is deposited at high growth temperatures (>700°C), where the misfit strain is 0.65% compressive, i.e., about 0.28% greater than the 0.37% misfit compressive strain at room temperature. At the high growth temperature, a 1 μm thick epilayer of GaP on Si is mostly relaxed, but subsequent cool down to room temperature results in crystal cracking problems.

It is precisely this crystal cracking problem due to the difference in the thermal expansion co-efficients of Si and GaP that the invention recited in claims 77 – 83 address.

See Specification, page 18, lines 26 – 28, page 19, lines 1 – 9, and page 21, lines 5 – 28. Thus independent claim 77 does not simply recite practicing GaP:N:Bi material as a solar cell with a silicon substrate. On the contrary, amended claim 77 now recites not only depositing a thin film of GaP at a temperature of at least 700°C on the Si crystal lattice to achieve two-dimensional growth of polar GaP on non-polar Si, but also:

> . . . prior to cooling the thin film of GaP and the Si crystal lattice to room temperature, isoelectronically co-doping the thin film of GaP with a deep acceptor element and a deep donor element in a proportion that reduces compressive misfit strain of the GaP on the Si crystal lattice, then cooling the isoelectronically co-doped thin film of GaP and the Si crystal lattice to room temperature as the misfit compressive strain reduces to a residual misfit strain of isoelectronically co-doped GaP on the Si crystal lattice at room temperature that is of lesser magnitude than the compressive misfit strain of the GaP on the Si crystal lattice would be without such isoelectronic co-coping.

See amended claim 79.

Kuznetsov, et al., do not show or suggest anything about how to fabricate thin film GaP semiconductor material on an Si crystal lattice in a manner that avoids crystal cracking. They never even discuss crystal lattice matching or mismatching of GaP or GaP:N:Bi in general, let alone in relation to Si and the problems relating to cracking when thin films of GaP are deposited on Si crystal lattices.

On the contrary, Kuznetsov, et al., prepared their samples of GaP:N:Bi by liquid epitaxy on GaP substrates, so they did not even encounter, let alone address, problems due to lattice mismatch and differences in thermal expansion coefficients. See Kuznetsov, et al., page 417, column 1, second paragraph. Therefore, amended claim 77 is believed to be clearly allowable over Kuznetsov, et al., under 35 U.S.C. § 103(a).

Dependent claims 78 and 80 – 82 are believed to be allowable for similar reasons to those explained above regarding claim 77, and further, because the additional features recited in those claims are not taught or fairly suggested by Kuznetsov, et al., either. Claim 79 has been cancelled, because it appears to be redundant and does not further narrow amended claim 77. Therefore, claim 81 is also amended to depend from claim 77, instead of from claim 79.

With allowance of claims 77 – 78 and 80 – 82 for the reasons explained above, the examiner's objection to dependent claim 83 will be moot.

Regarding claim 84:

Claim 84 has already been allowed.

Regarding claims 85 – 88:

Claim 85 has been amended in a manner similar to amended claim 1 to recite that the Group III – V semiconductor compound or alloy is modified to have a lower effective bandgap by the isoelectronic co-doping with deep acceptor and deep donor elements, which clearly distinguishes this claimed invention from Kuznetsov, et al., for the reasons explained above regarding claim 1. In short, as explained above, there was no modification of the effective bandgap of GaP by Kuznetsov, et al., and there was not even a suggestion in Kuznetsov, et al., that bandgap modification of GaP was possible or even desirable. As also explained above, the light emission reported by Kuznetsov, et al., occurred from donor-acceptor like transitions and not from band-to-band transitions, and the concentrations of N reported by Kuznetsov, et al., in their studies were at least an order of magnitude too small to provide sufficient overlapping wavefunctions to merge with band edges, to modify the effective bandgap, or to result in direct bandgap-like behavior. Thus, the Kuznetsov, et al., doping of GaP with N in the presence of Bi and the light emissions from donor-acceptor like transitions in the Kuznetsov, et al., report are virtually irrelevant to the applicant's claimed LED's and lasers in which effective bandgaps of semiconductor compounds or alloys are modified and emissions are from band-to-band transitions.

Therefore, claim 85 as now amended is believed to be clearly allowable under 35 U.S.C. § 103(a) over Kuznetsov, et al. Dependent claims 86 – 88 are also believed to be allowable under 35 U.S.C. § 103(a) over Kuznetsov., et al., for the same reasons.

Regarding claims 89 – 105:

With allowance of claims 85 – 88 for the reasons explained above, the examiner's objections to claims 89 – 105 will be moot.

Regarding claims 106 – 118:

Claims 106 – 188 have already been allowed.

Regarding claims 119 – 120:

Claims 119 and 120 were rejected by the examiner for the same reasons as claims 85 – 88. Consequently, independent claim 119 has been amended in a manner similar to the amendment of claim 85, i.e., to recite the bandgap modification by isoelectronic co-doping, which is not shown or suggested by Kuznetsov, et al. Therefore, amended independent claim 119 and dependent claim 120 are believed to be allowable for the same reasons as explained above regarding claims 85 – 88.

Regarding claims 121 – 131:

With the allowance of claims 119 – 120 for the reasons explained above, the examiner's objections to claims 121 – 131 will be moot.

Regarding claims 132 – 135:

Claims 132 – 135 were rejected by the examiner for similar reasons as claims 59 – 65, 85 – 88, and 119 – 120, with the additional assertion that it would have been fundamentally obvious to have practiced a photodiode of Kuznetsov material on a III – V substrate to integrate with other devices or reduce cost. Consequently, the applicant has now amended independent claim 132 in a manner similar to the amendment of claims 85 and 119, i.e., to recite the bandgap modification by isoelectronic co-doping, which is not shown or suggested by Kuznetsov, et al. Therefore, amended independent claim 132 and dependent claims 133 – 135 are believed to be allowable for the same reasons as explained above regarding claims 85 – 88. Further, regarding dependent claims 133 – 135, neither Kuznetsov, et al., nor any of the other prior art cited shows or suggests anything about GaAs being isoelectronically co-doped with N and Bi for use as an active junction of a photodiode, let alone one in which the effective bandgap is lowered by the isoelectronic co-doping.

Regarding new claim 136:

The new claim 136 recites "isoelectronically co-doping . . . at sufficiently high concentrations to form at least one impurity band that merges with one of the conduction and valance bands . . . ." As discussed above, such merging between an impurity band and the conduction band or valence band is a mechanism by which the bandgap of the host semiconductor is modified. Such bandgap modification is not taught or suggested by any

prior art. Thus, the applicant respectfully submits that new claim 136 is allowable and requests that the examiner allow it.

The applicant respectfully submits that all of claims 1 – 78 and 8 - 136, as amended, are allowable under both 35 U.S.C. § 102(b) and 35 U.S.C. § 103(a) and requests that a timely Notice of Allowance be issued in this case. If any issues remain to be resolved, the examiner is requested to contact applicant's attorney at the telephone number listed below.

Date: 11/15/02

Respectfully Submitted,

Paul J. White

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Markup Version Of The Amended Specification

Please replace the paragraph beginning on page 3, line 12, with the following:

Another specific object of this invention is to fabricate and tailor semiconductor materials for active layers of LED's and laser diodes with bandgaps that produce light in wavelengths that are particularly suitable for fiber optic transmission, such as 1.55~~μm~~ μm or 1.3 ~~μm~~μm and which are lattice matched to common semiconductor substrate materials, such as Si or GaAs.

Please replace the paragraph beginning on page 6, line 9, with the following:

An example high efficiency, monolithic, quadruple junction, solar cell 10 constructed according to the principles and by a method of this invention is shown diagrammatically in Figure 1. An active, light-absorbing cell 12 comprising a dilute alloy of $GaAs_{1-x-y}N_xBi_{-y}$ (sometimes abbreviated as GaAs:N:Bi) with a bandgap of about 1.05 eV is positioned between a Ge cell 11 (bandgap of 0.67 eV) and a GaAs cell 13 (bandgap of 1.42 eV) in the monolithic, quadruple junction, solar cell 10, which also has a InGaP cell 14 (bandgap of 1.90 eV) overlaying the GaAs cell 13 and a Ge substrate 15, which is doped to provide a n-p junction 21 as the bottom Ge cell 11. Of course, the solar cell 10 also has a conventional bottom contact layer 16 and top grid 17 to facilitate electrical connection of the cell 10 into a circuit (not shown). Other conventional features, such as anti-reflective (A.R.) coating 19, window layer 25 (to passivate the surface), contact layer 18 (to facilitate ohmic contacts), and back surface reflectors (BSR) 26, 27, 28, 29, 30, are also shown, although these components are well-known in the art and are not part of this invention. The BSR layers 26, 27, 28, 29, 30 are designed to be lattice matched to, but with higher bandgaps than, the regions they surround.

Please replace the paragraph beginning on page 6, line 22, with the following:

When solar radiation 30 irradiates the solar cell 10, the higher energy, shorter wavelength portion of the solar spectrum (e.g., wave-lengths in a range of about 652 nm and below) is absorbed and converted to electric energy substantially in the top (fourth) cell 14 of InGaP, while the lower energy, longer wavelength solar radiation is transmitted into the next (third) cell 13 of GaAs. The next to highest energy range of solar radiation (wavelength of about 873 nm to 652

nm) is then absorbed and converted to electric energy substantially in the GaAs third cell 13, which also transmits lower energy solar radiation to the second cell 12 of GaAs:N:Bi. This GaAs:N:Bi second cell 12 is fabricated according to this invention, as will be explained in more detail below. Solar radiation in the range of about 1180 nm to 873 nm is absorbed and converted to electric energy substantially in this second cell 12, while the remaining unabsorbed, lower energy radiation is transmitted to the first or bottom cell 11 of Ge. The bottom cell 11 absorbs and converts solar radiation in a range of about 1850 nm to 1180 nm to electric energy. Therefore, a monolithic, quadruple junction, solar cell 10 constructed as described above can absorb and convert enough of the solar radiation spectrum to electric energy to approach an overall cell efficiency of 40% AM1.

Please replace the paragraph beginning on page 8, line 1, with the following:

The GaAs:N:Bi alloy used for the second cell 12 is fabricated by isoelectronic co-doping the GaAs alloy with both nitrogen (N) and bismuth (Bi), preferably simultaneously. While the giant conduction band bowing observed by Weyers *et al* in $GaAs_{1-x}N_x$ appeared to demonstrate that the addition of N to GaAs can reduce the bandgap of GaAs significantly, and while the subsequent fabrication of the $Ga_{0.92}$-$In_{0.08}$-$N_{0.03}$-$As_{0.97}$ alloy by Kondow, et al., utilized that concept to fabricate a semiconductor material with the desired 1.0 eV bandgap, a significant part of this invention and the motivation for the solutions, processes, and devices described herein is the realization of the following: (i) that, unfortunately, the N in the alloy also creates isoelectronic traps, which have defeated all attempts to utilize such giant bowing of the conduction band; and (ii) that the N in the GaAs does not just induce the bowing of the conduction band of GaAs, but, instead, the N impurities participate directly in the formation of the conduction band via the formation of a deep acceptor N impurity band. A further significant part of this invention includes the discoveries that: (i) Isoelectronic co-doping of GaAs with both N and Bi simultaneously also creates a deep donor; and (ii) The effect of such deep donors on the valence band mirrors the effect of N on the conduction band and virtually eliminates the adverse effects of the N-based isoelectronic traps that have previously defeated use of the otherwise beneficial

effects (e.g., bandgap reduction) of N in GaAs semiconductor materials used as photocells. Specifically, such isoelectronic co-doping of GaAs with both N and Bi virtually eliminates the very poor electron mobilities and hopping-like transport characteristics, which are inherent in GaAs that is doped only with N, and it counteracts the increased Madelung energy effects of N in the GaAs crystal lattice that limit solubility of the N in the GaAs material. Such co-doping with N and Bi is isoelectronic, because both N and Bi are in the same group on the periodic table of the elements as the host elements they replace.

Please replace the paragraph beginning on page 13, line 18, with the following:

On isoelectronically co-doping GaAs with N and Bi, the bandgap reduction due to the conduction band E_c bowing generated by the N doping is reinforced or enhanced by the addition of the Bi, which has an analogous effect on the valence band. At the same time, GaAs:N:Bi can be lattice matched to GaAs, which makes it compatible and useable as an active cell component 12 adjacent a GaAs cell component 13 in a multi-junction solar cell, such as the monolithic, quadruple junction solar cell 10 illustrated in Figure 1. Further, since the solubility of both N and Bi in GaAs is enhanced by almost a factor of 10 by isoelectronic co-doping of the GaAs with N and Bi over the solubility of either N or Bi alone in GaAs, and since the carrier mobilities are enhanced by almost a factor of 15, GaAs:N:Bi with bandgaps lower than 1.0 eV—--actually, anywhere in a range of less than 1.42 eV down to 0.8 eV—--lattice matched to GaAs can be fabricated according to this invention by selecting desired concentrations and proportions of N and Bi to obtain the desired specific bandgap and lattice matching, as is well within the capabilities of persons skilled in the art once they understand the principles of this invention.

Please replace the paragraph beginning on page 14, line 18, with the following:

However, when a large number of the isoelectronic dopant atoms are introduced into the host crystal lattice, i.e., more than about $10^{19\text{-}\cancel{cm}}$ cm^{-3}, the interaction between neighboring dopant atoms, i.e., ~~"~~pair interaction, triplet interaction, etc., in turn generates impurity bands. For heavy doping, such as is used for N (or Bi) in GaAs or in GaP, it is these various impurity levels generated by the impurity interactions that generate "bound states" whose energy levels merge with the conduction band (or valence band in the case of Bi), and such merger gets manifested as the bandgap bowing.

Please replace the paragraph beginning on page 15, line 25, with the following:

The impurity levels introduced by normally used charged acceptors, such as impurity level 42 illustrated in Figure 2, are located typically a few meV, ~~i.~~e.g., about 20 meV, above the valence band edge E_v. Likewise, impurity levels introduced by normally used charged donors, such as impurity level 44 illustrated in Figure 3, are typically a few meV~~,~~ below the conductor band edge E_c. If the depth of these levels introduced by impurities were to be greater than the room temperature Boltzmann energy kT = 26 meV, then most of the dopants would not be ionized at room temperature, thus would not behave as acceptors or donors. Impurity levels induced by charged acceptors or donors that are much deeper than 26 meV are referred to as deep levels.

Please replace the paragraph beginning on page 16, line 22, with the following:

Referring again to Figure 1, Ge can be used for the bottom or first cell 11 in the monolithic, quadruple junction solar cell 10 to provide the desired 0.67 eV bandgap for the solar cell 10, because the isoelectronically co-doped GaAs:N:Bi alloy of this invention can be grown nearly lattice matched with Ge, i.e., within about 0.2% misfit strain, to provide sufficient durability and carrier mobility for an efficient solar cell device. While Ge has an indirect bandgap, it is still suitable for the bottom cell 11 when used as a substrate 15 that also incorporates the Ge bottom cell 11, because the substrate 15 provides sufficient thickness for the Ge cell 11 to absorb substantially all the light in the 1850 nm to 1180 nm wavelength range.

Please replace the paragraph beginning on page 17, line 3, with the following:

Any known procedure for co-doping, which is well-known in the art, can be used to accomplish the isoelectronic co-doping of alloys according to this invention, such as sequential bombardment of GaAs with N and Bi to implant overlapping N and Bi dopant profiles in the GaAs or by using OMVPE (organo-metallic vapor phase epitaxy) growth techniques. A suitable organic source for Bi—trimethylbismuth—is available commercially, for example, from Rohm and Haas of North Andover, Massachusetts.

Nitrogen can be obtained from dimethylhydrazine, as is also well-known to persons skilled in the art, which can be obtained from the same company. The co-doping can also be achieved using molecular beam epitaxy (MBE) growth, vapor phase epitaxy (VPE) growth, or Liquid Phase Epitaxy growth (LPE). Co-doping using ion-implantation techniques are described, for example in S.P. Witrow *et al.*, "Ion Beam Annealing of Si Co-Implanted with Ga and As", *Mat. Res. Soc. Symp. Proc.*, Vol. 57, pp. 143-148, 1990, which is a current definitive, state-of-the-art reference and authority on co-doping, as well as in several other articles published since 1990. Also, as mentioned above, this invention is not limited to isoelectronic co-doping of GaAs with N and Bi. For example, but not for limitation, InP, GaP, InGaAs, and ZnSe can also be isoelectronic co-doped with "deep" acceptors and "deep" donors with similar benefits as those described above for GaAs alloys.

Please replace the paragraph beginning on page 18, line 4, with the following:

Referring to Figure 5, a two-junction tandem solar cell 50 according to this invention has a Si substrate 52, which is doped to provide a n-p junction 55, as is well-known to persons skilled in the art, to function as the bottom cell 54 with a bandgap of 1.1 eV. It also has a top cell 58 of isoelectronic co-doped GaP:N:Bi alloy according to this invention, which has a bandgap of 1.75 eV. The GaP:N:Bi alloy is charge doped with an acceptor, such as Zn or Cd, and with a donor, such as S or Se, to form a n-p junction 59. A tunnel junction 56 of n^{++}– and p^{++}—doped Si is also provided between the bottom cell 54 and the top cell 58, as is within the capabilities of persons skilled in the art. Of course, the junctions 55, 59 could be inverted to p - n junctions, and the p^{++}–n^{++} tunnel junction 56 could be inverted to a n^{++}-p^{++} tunnel junction, as would be within the capabilities of persons skilled in the art. Of course, a bottom contact 60 and grid contacts 62 are provided to connect the solar cell 50 into an electric circuit (not shown); as is also within the capabilities of persons skilled in the art. The back surface reflector (BSR) 63, anti-reflection coating (ARC) 49, window layer 61, and contact layer 63 are conventional and well-known to persons skilled in the art and not part of this invention.

Please replace the paragraph beginning on page 22, line 1, with the following:

The example two-junction tandem solar cell 50 illustrated in Figure 5, utilized isoelectronic ~~de~~co-doped GaP:N:Bi with a bandgap of about 1.75 eV (1.65 eV to 1.85 eV) according to this invention to fabricate the second or top cell 58 on the Si bottom cell 54 (fabricated on a Si substrate 52), which has a bandgap of about 1.1 eV. The top cell 58 absorbs light energy in a wavelength range of about 708 nm and below and converts it to electricity, while the bottom cell 54 absorbs light energy in a wavelength range of about 1127 nm to 708 nm and converts it to electricity.

Please replace the paragraph beginning on page 22, line 7, with the following:

The example three-cell tandem solar cell 70 illustrated in Figure 6 has a Si first or bottom cell 74 fabricated on a Si substrate 72 with n - p or p - n doped active junction 75 and a bandgap of about 1.1 eV, similar to the bottom cell 54 in solar cell 50 described above. Also, a p^{++}–n^{++} or n^{++}—p^{++} Si tunnel junction 76 similar to the tunnel junction 56 in solar cell 50 is provided over the bottom cell 74. An isoelectronic co-doped GaP:N:Bi semiconductor alloy according to this invention with a bandgap of about 1.55 eV (1.45 eV to 1.65 eV) is utilized for the second cell 78. In general, the higher the concentration of the isoelectronic co-dopants, the lower the effective bandgap of the resulting isoelectronically co-doped semiconductor alloy. Therefore, once persons skilled in the art understand this invention, they will be able to tailor any of the semiconductor alloys discussed herein to the desired bandgaps. The GaP:N:Bi second cell 78 is charge doped to provide a n—p or a p—n junction 79, as described above for the second cell 58 of solar cell 50, a more heavily doped tunnel junction 80 is provided over the second cell 78 and a BSR layer 85, as will be understood by persons skilled in the art. A third or top cell 82 of isoelectronic co-doped GaP:N:Bi alloy with a bandgap of about 2.05 eV (1.95 eV to 2.15 eV) according to this invention is provided over the second cell 78, tunnel junction 80, and BSR layer 84. The GaP:N:Bi top cell is charged doped to form a n—p or p—n junction 83 similar to the doping for the junction 79 in

the second cell 78, as will be understood by persons skilled in the art. A bottom contact 90 and top grid contacts 92 are also provided, as will be understood by persons skilled in the art.

Please replace the paragraph beginning on page 22, line 24, with the following:

The top cell 82 of the solar cell 70 absorbs light energy in a wavelength range of about 605_nm and below and converts it to electricity, while the second cell 78 and bottom cell 75 absorb light energy in respective wavelength ranges of 605_nm to 800_nm and 800_nm to 1127 nm and convert it to electricity.

Please replace the paragraph beginning on page 23, line 15, with the following:

Since, in principle, a solar cell is just an LED (light emitting diode) operating in reverse, GaAs co-doped with isoelectronic deep acceptors and deep donors, such as N and Bi, according to this invention, can also be used to provide simpler and less expensive LEDs and laser diodes than the current state of the art InGaAsP devices for signal generation in wavelengths that are most efficient, therefore preferred, for fiber optic transmission. A laser diode is basically an LED, which includes quantum and optical confinement structures to produce a very narrow, intense beam of coherent light. Therefore, unless indicated otherwise, references herein to LEDs are meant to also include laser diodes. Fiber optic communications of voice, video, and digital data is based on silica optical fibers, which, for single mode, long haul transmission applications, have the highest bandwidth and lowest attenuation in a wavelength range or "window" centered around 1.55_µm. This low loss wavelength transmission window of silica optical fiber also matches the maximum in the gain bandwidth for erbium-doped fiber amplifiers. As mentioned above, prior to this invention, the optimal signal generation sources for this 1.55_µm wavelength were InGaAsP quaternary alloy based semiconductor laser diodes grown on InP substrates.

Please replace the paragraph beginning on page 24, line 1, with the following:[52]

Photoelectric production of 1.55µm light requires a semiconductor bandgap of about 0.8 eV. GaAs (1.42 eV) can be isoelectronically co-doped with isoelectronic deep acceptors and deep donors according to this invention to lo[53]wer the bandgap of GaAs to create semiconductor materials with effective bandgaps corresponding to about 0.8 eV (0.7 eV to 0.9 eV). For example, GaAs (1.42 eV) can be isoelectronically co-doped either with N and Bi to create

GaAs:N:Bi with an effective bandgap of about 0.8 eV. Therefore, this isoelectronic co-doped material can be used as an active layer for LED, including laser diode, structures to generate light with a wavelength of about 1.55 μm. Similarly, photoelectric production of 1.3 μm light requires a semiconductor bandgap of about 0.95 eV, which can be achieved by isoelectronically co-doping GaAs with deep acceptors and deep donors according to this invention.

Please replace the paragraph beginning on page 24, line 10, with the following:

As shown in Figure 7, isoelectronic co-doping, according to this invention, can also be used to fabricate semiconductor diode edge-emitting lasers 120 on GaAs substrates, which operate in the 1.55 or 1.3 μm wavelength regions for fiber-optic network communications. An n-type $GaInP_2$ cladding layer (low refractive index optical confining layer) 126 is grown lattice matched over an n-type GaAs substrate 124 followed by a bottom GaAs separate confinement heterostructure (SCH) layer 127. The active region 128 (see inset in Figure 7) comprises a set of multiple quantum wells (MQW) 135 of isoelectronically co-doped GaAs:N:Bi:In, where each well is surrounded by GaAs barriers 136. The amount of isoelectronic co-doping of the MQW's 135 and the MQW 135 well widths are chosen to yield ground state transition energies near 0.8 ~ 0.93 eV (1.55 or 1.3 μm). The In is added to provide an additional parameter for lattice matching so that the N to Bi ratio can be adjusted independently for optimally regularizing the behavior of the alloy. The GaAs top SCH layer 129 is then grown followed by the top p-type GaInP~~2~~$_2$ cladding layer 130 and a top contact stripe 132. The overall structure 120 is that of a p-i-n diode. When a voltage is applied to the top contact 132 and bottom contact 122 to forward bias the p-i-n diode, the barriers 136 in the MQW's 135 provide quantum confinement for the electrons and holes injected from the n (126) and p (130) regions, respectively, under the forward bias into the active region 128. The cladding layers 126 and 130 provide optical confinement for the radiation emitted as a result of the recombination of the injected electrons and holes in the MQW's 135. The thickness of the top and bottom separate confinement heterostructure (SCH) layers 127 and 129 is of the order of an optical wavelength, thereby confining in the

transverse direction the optical Fabry-Perot cavity bounded longitudinally by the front and rear mirrors formed by the cleaved faces 133 and 131 respectively. The mirrors may be coated to increase or decrease their reflectivity as necessary or desired to produce and emit a laser light beam 134, as is understood by persons skilled in the art. Carrier flow in the vertical direction follows the contour defined by the lateral stripe shape of the top contact 132. Thus, the lasing area is limited in the lateral direction to the stripe region defined by the top contact 132 because of gain guiding. Details such as contact layers for low resistance contacts and buffer layers are not shown. The edge-emitting laser in Figure 7 illustrates the most basic edge-emitting laser configuration. Other means of defining the stripe geometry for limiting the lateral width of the lasing area can be used such as those employed for the ridge-waveguide laser configuration or by using index guiding as for the buried heterostructure (BH) laser configuration, or by forming mesa or inverse mesa geometry structures. Many techniques, such as the use of reverse biased diodes as lateral current blocking layers, or oxide or polymide insulating layers or deeply etched recesses for lateral isolation and lowering of parasitic capacitances, can be used as is within the capabilities of persons skilled in the art. Also, as is well within the capabilities of persons skilled in the art, by inserting a grating profile layer at the bottom or top interface of the cladding layers 130 or 126, a DFB (distributed feedback) laser or DBR (distributed Bragg reflector) laser can be realized, which has a very narrow frequency spectrum suitable for fiber-optic communications. Finally, any of the conventional growth techniques, such as MBE, MOCVD, VPE, or LPE (liquid phase epitaxy), can be used for the growth of the device, and the charged doping for n and p type layers, which is achieved by conventional techniques, can be interchanged.

<u>Please replace the paragraph beginning on page 26, line 7, with the following:</u>

Isoelectronically co-doped GaAs, according to this invention, can also be used to fabricate VCSEL's (Vertical Cavity Surface Emitting Lasers) 180 to operate in the 1.55 μm or 1.3 μm wavelength regions, as shown in Figure. 8. A DBR (distributed Bragg reflector)

stack 187 comprising n-type GaAs/$Al_xGa_{1-x}As$ alternating layers is grown over an n-type GaAs substrate 188. The topmost layer 186 of the stack is made Al-rich. Next the bottom SCH layer 191 is grown using GaAs. This bottom SCH layer 191 is followed by growth of the active layer 185 (see inset) which comprises a set of multiple quantum wells (MQW) 193 of isoelectronically co-doped GaAs:N:Bi:In, where each well 193 is surrounded by GaAs barriers 194. The amount of isoelectronic co-doping of the MQW's 193 and the MQW 193 well widths are chosen to yield ground state transition energies near 0.8 ~ 0.93 eV (1.55 or 1.3 μm). The top SCH layer 190 is next grown using GaAs followed by a DBR stack 183 comprising p-type GaAs/$Al_xGa_{1-x}As$ alternating layers. The bottommost layer 184 of the DBR stack 183 is made Al-rich. A front metallic contact 182, and a back metallic contact 189 complete the growth. Any of the conventional methods that are well known to persons skilled in the art can be next used to expose the vertical cross-section of the device 180 to a steam environment at a temperature of 400 ~ 450 °C for a time designed to oxidize the Al-rich layers 184 and 186 in the DBR stacks 183 and 187 from the periphery, leaving a central, un-oxidized window region through which laser light 181 emanates. The resulting oxidized aperture layer 184, 186 serves as a current blocking layer (CBL). The p-type and n-type regions are obtained by charge doping of GaAs and $Al_xGa_{1-x}As$. The charged doping for the p-type and n-type regions are achieved by conventional techniques and of course the p-type and n-type regions can be interchanged. Other geometries for a VCSEL laser, which require other methods for generating the current blocking, which is the function of oxidized layers 184 and 186, can also be utilized as is within the capabilities of persons skilled in the art. Also, since utilizing two relatively low n-type DBR mirror stacks (instead of one p-type and one n-type as in Figure 8) reduces the free carrier absorption, which can be excessive at long wavelengths in p-type materials, this can be achieved by introducing a tunnel junction into the high index GaAs layer nearest to the optical cavity 185 in the top output mirror 183. Finally any of the conventional growth techniques, such as MBE or MOCVD, can be used for the growth of the device. Prior to this invention, only VCSEL lasers operating around the

800 nm near-infrared wavelength range were commercially available, because it is very difficult to fabricate the 1.55 μm and 1.3 μm wavelength devices. This limitation is due to the fact that these devices are generally based on the quartenary InGaAsP alloy system that could only be grown lattice matched to InP substrates, and it is very difficult to grow decent DBR stacks using this quartenary alloy. Thus, the InGaAsP based 1.55 and 1.3 μm lasers are generally of the edge-emitting type instead of the VCSEL type. Since VCSEL lasers offer unique advantages over edge emitting lasers, and GaAs technology is cheaper than InP technology, isoelectronic co-doping of GaAs according to this invention to fabricate the VCSEL 180 proves very advantageous. In addition, the isoelectronically co-doped laser 180 described above has the following advantages:

Please replace the paragraph beginning on page 29, line 3, with the following:

As shown in Figure 10, isoelectronic co-doping according to this invention can also be used to grow Red/–NIR, i.e., 640 - 800 nm wavelength, LED's 210 monolithically on silicon. The isoelectronically co-doped system of the LED 200 described above and illustrated in Figure 9 can also be grown on a Si substrate 217, as shown in Figure 10, using a step-graded layer structure 216 to allow for accommodation of the 0.37% compressive mismatch strain between the GaP based DH configuration 219 and the Si substrate 217. As shown in Figure 10, a step-graded layer structure 216 is first grown over the silicon substrate 217 to accommodate the 0.37% compressive mismatch strain between the GaP based double heterostructure laser 219 with the Si substrate 217. This step-graded layer structure 216 comprises four layers of n-doped $GaP_{1-x-y}N_xBi_y$ grown consecutively over the Si substrate 217 with the composition of N and Bi for each layer adjusted such that the mismatch strain between adjacent layers is about 0.1% for the first three layers, and is about 0.07% between the third and fourth layer of the step graded layers 216. The thickness of the first three layers of the step graded layers 216 is roughly 0.3 μm and that of the fourth layer is 0.8 μm. This arrangement allows the final network of misfit dislocations arising from the last composition step-grade to evolve fully, leaving only a very low density of threading dislocations to

propagate into the DH configuration layers 219. The active region 214 in this LED 210 can also be either a MQW structure, as shown in Figure 10, or it can be a single isoelectronically co-doped GaP:N:Bi layer (not shown) for lower cost, albeit lower energy emission, LED devices. An MQW structure for the active region 214 comprises multiple, alternating GaP barrier layers 221 and isoelectronically co-doped GaP:N:Bi well layers 222, which provide quantum confinement to shift LED emission toward higher energies and lower threshold current as compared to a single GaP:N:Bi layer active region. The p-GaP superstrate 212, the DH configuration layers 219, comprising either the single GaP:N:Bi layer active region 214 (not shown) or the MQW active region 214 comprising the multiple, alternating GaP barrier layers 221 and isoelectronically co-doped GaP:N:Bi well layers 222, as well as the p-GaP barrier layer 213 and the n-GaP barrier layer 215, can be grown in a manner that is analogous to the superstrate layer 208 and the DH layer 206 discussed for Figure 9. However, in contrast to the High Brightness LED 200 of Figure 9, since the Si substrate 217 of the LED 210 in Figure 10 is not transparent to the light produced in the active region 214, and, instead will absorb such light. Therefore, only the top and side cones of light emitted from the DH configuration 219 can be extracted. The unique advantage of the LED 210, however, is that it can be grown monolithically on Si, thereby allowing for such devices to be integrated directly with electronic circuits that have been fabricated alongside monolithically. Such monolithic integration of photonics and electronics would be very suitable for applications, such as in integrated transceiver chips for fiber-optic communications and for microdisplays. Further, while it is not necessary to this invention, the disadvantage of light absorption by the Si substrate 217 can be mitigated, and the efficiency of the LED 210 can be enhanced, by forming a distributed Bragg reflector (DBR) 120 comprising multiple, alternating layers of AlP and GaP between the barrier layer 215 and the step-graded layers 216 to reflect light back through the DH structure 219 and superstrate 212 before it reaches the light-absorbing Si substrate 217. Therefore, such reflected light emanates from the front surface of the LED 210 to enhance the energy and brightness of the emitted light instead of

being absorbed by the Si substrate 217 and lost as heat. Also, if the LED 210 is to be coupled to an optical fiber (not shown), then the front contact 211 can be moved from the center to the edges, a recess for the fiber (not shown) can be etched into the superstrate 212, and an oxide isolation layer (oxide layer with a central aperture, which could be realized by oxidization of an inserted AlP layer from the periphery) can be inserted between layers 215 and 216 to limit the emitting area of the laser to the area under the fiber.

Please replace the paragraph beginning on page 32, line 1, with the following:

The edge-emitting laser 230 in Figure 11 illustrates the most basic edge-emitting laser configuration. The alloy composition of the SCH layers 233, 243 may be linearly, parabolically, or step graded as in GRINSCH (graded index separate confinement heterostructure) lasers (here one would use $Al_xGa_{1-x}P$ for the cladding layers 232, 234 and grade the composition of x from $x = 0$ to the value of x in the cladding layers 232, 234). Other techniques of defining the stripe geometry for limiting the lateral width of the lasing area can also be used, such as those employed for the ridge-waveguide laser configuration or by using index guiding as for the buried heterostructure (BH) laser configuration or by forming narrow mesas or inverse mesa geometry structures. Many techniques, such as the use of reverse biased diodes as lateral current blocking layers, or oxide or polymide insulating layers or deeply etched recesses for lateral isolation and lowering of parasitic capacitances, can be used as is within the capabilities of those familiar with the art. Also, as is well within the capabilities of those familiar with the art, by inserting a grating profile layer at the bottom or top interface of the cladding layers 232 or 234, a DFB (distributed feedback) laser or DBR (distributed Bragg reflector laser) can be realized which has a very narrow frequency spectrum suitable for fiber-optic communications. Finally, any of the conventional growth techniques, such as MBE or MOCVD or VPE or LPE, can be used for the growth of the device, and the charged doping for n-type and p-type layers, which is achieved by conventional doping techniques, can be reversed.

Markup Version of Amended Claims

1. (Amended) A method of modifying a semiconductor compound or alloy comprising host atoms in a host crystal lattice to have a lower effective bandgap than the semiconductor compound or alloy has prior to modification, the method comprising:

isoelectronically co-doping the semiconductor compound or alloy with a sufficient combination of a first isoelectronic dopant comprising atoms that form isoelectronic electron traps in the host crystal lattice that behave as deep acceptors and ~~with~~ a second isoelectronic dopant comprising atoms that form isoelectronic hole traps in the host crystal lattice that behave as deep donors to lower the effective bandgap of the semiconductor compound or alloy.

2. (Amended) A method of modifying a semiconductor compound or alloy comprising host atoms in a host crystal lattice to have a lower effective bandgap than the semiconductor compound or alloy has prior to modification, comprising:

~~2. The method of claim 1, including~~ isoelectronically co-doping the semiconductor compound or alloy with a first isoelectronic dopant comprising atoms that form isoelectronic electron traps in the host crystal lattice that behave as deep acceptors and with a second isoelectronic dopant comprising atoms that form isoelectronic hole traps in the host crystal lattice that behave as deep donors, such that content of the first isoelectronic dopant in the semiconductor compound or alloy is more than 1 at.% and content of the second isoelectronic dopant in the semiconductor compound or alloy is more than 1 at.%.

29. (Amended) A method of modifying a semiconductor compound or alloy comprising host crystal atoms in a host crystal ~~lattice~~ to have a lower effective bandgap than the semiconductor compound or alloy has prior to modification, the method comprising:

isoelectronically co-doping the semiconductor compound or alloy with a sufficient combination of a first isoelectronic atomic species and a second isoelectronic atomic species to lower the effective bandgap of the semiconductor compound or alloy,

wherein said first isoelectronic atomic species is sufficiently different in electronegativity, size, and pseudo potential difference from host crystal atoms that are ~~substrituted~~substituted by the first isoelectronic atomic species to generate an isoelectronic trap whose impurity potential is sufficiently deep and of a very short range to behave as acceptors, and

wherein said second isoelectronic atomic species is sufficiently different in electronegativity, size, and pseudo potential difference from host crystal atoms that are substituted by the second isoelectronic atomic species to generate an isoelectronic trap whose impurity potential is sufficiently deep and of a very short range to behave as donors.

30. (Amended) A semiconductor material for use as an active cell in a semiconductor device, the material comprising:

a semiconductor compound or alloy comprising host atoms in a host crystal lattice with an effective bandgap that is ~~isoelectronically~~modified by isoelectronic co~~-doped~~-doping with a sufficient combination of a first isoelectronic dopant comprising atoms that form isoelectronic traps in the host crystal lattice that behave as deep acceptors~~,~~ and ~~with~~ a second isoelectronic dopant comprising atoms that form isoelectronic traps in the host crystal lattice that behave as deep donors to lower the effective bandgap of the semiconductor material.

77. (Amended) A method of fabricating thin film GaP semiconductor material on a Si crystal lattice, comprising:

depositing a thin film of GaP at a temperature of at least about 700 ~~o~~°C on the Si crystal lattice to achieve two-dimensional growth of polar GaP on non-polar Si;~~and~~

prior to cooling the thin film of GaP and the Si crystal lattice to room temperature, isoelectronically co-doping the thin film of GaP with a deep acceptor element and a deep donor element in a proportion that reduces compressive misfit strain of the GaP on the Si crystal lattice; and

cooling the thin film of isoelectronically co-coped thin film of GaP and Si crystal lattice to room temperature as the misfit compressive strain reduces to a residual misfit strain

of the isoelectronically co-doped GaP on the Si crystal lattice at room temperature that is of lesser magnitude than the compressive misfit strain of the GaP on the Si crystal lattice would be without such isoelectronic co-doping.

81. (Amended) The method of claim ~~79,~~77, including isoelectronically co-doping the GaP with sufficient deep acceptor element and deep donor element to change compressive lattice mismatch between the GaP and the Si to enough tensile lattice mismatch to offset additional compressive lattice mismatch strain that occurs while heating the Si crystal lattice and depositing GaP at a temperature of about 700 °C.

85. (Amended) A light-emitting diode, comprising:

an active layer of Group III - V semiconductor compound or alloy that is modified to have a lower-effective bandgap by isoelectronically co-~~doped~~doping the Group III – V semiconductor compound or alloy with sufficient concentrations of a deep acceptor element and a deep donor element to produce the lower effective bandgap, said active layer being sandwiched between: (i) a first barrier layer of the Group III - V semiconductor compound or alloy charged-doped to either n-type or p-type; and (ii) a second barrier layer of the Group III - V semiconductor alloy charged-doped to either n-type or p-type, whichever is opposite the charge-doped first barrier layer.

119. (Amended) A laser diode, comprising:

an active region comprising a set of ~~isoelectronically co-doped~~ Group III – V semiconductor compound or alloy MQW layers that are modified to have lower effective bandgaps by isoelectronically co-doping the MQW layers of Group III – V semiconductor compounds or alloys with sufficient concentrations of a deep acceptor element and a deep donor element to produce the lower effective bandgaps, said MQW layers being separated by barrier layers of Group III - V semiconductor compound or alloy, said active region being sandwiched between a bottom SCH layer of Group III - V semiconductor compound or alloy and a top SCH layer of Group III - V semiconductor compound or alloy;

a bottom cladding layer of group III - V semiconductor compound or alloy underlaying the bottom SCH layer; and

a top cladding layer of Group III - V semiconductor compound or alloy overlaying the top SCH layer.

132. (Amended) A photodiode, comprising:

an active junction of Group III - V semiconductor compound or alloy, which is modified to have a lower effective bandgap by isoelectronically co-~~doped~~ doping the Group III - V semiconductor compound or alloy with sufficient concentrations of a deep acceptor element and a deep donor element to produce the lower effective bandgap, and which is fabricated on a substrate of Group III - V semiconductor compound or alloy.

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